

Abundance and survival rates of green turtles in an urban environment: coexistence of humans and an endangered species

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Abstract Longitudinal capture-mark-recapture data were used to estimate abundance and survival rates for green turtles (*Chelonia mydas*) in San Diego Bay, California, USA. These turtles were closely associated with warm effluent from a power plant during winter months. The life stage distribution of green turtles in the bay ranged from post-pelagic juveniles to adults (44.0–110.4 cm straight carapace length). During 99 capture sessions between December 2, 1990, and March 25, 2009, 96 individual green turtles were caught. To estimate abundance and survival rates, robust-design mark-recapture models were fitted to capture-recapture histories using software MARK. The estimated annual survival rate was 0.861 (SE = 0.147, 95% CI = 0.356–0.986), whereas annual abundance ranged from 16 (SE = 6.3, 95% CI = 4–29) to 61 (SE = 13.2, 95% CI = 36–88). This study provides the first survival rate and abundance estimates for a green turtle foraging population in the highly industrialized San Diego Bay.

Introduction

Marine turtle populations have declined precipitously in the last few decades, and many populations may face

extirpation (Jackson 1997; National Research Council 1990). Anthropogenic factors, such as habitat degradation, direct harvest, and incidental mortality from fishing operations, are the main causes of the declines (National Research Council 1990). Because of their life history characteristics (long-lived, high mortality in the early life stages, and delayed sexual maturity), marine turtle populations do not respond to management interventions quickly. Conservation efforts at nesting beaches during the last 30 years may have resulted in increasing trends for some populations, e.g., green turtles, *Chelonia mydas*, at several nesting beaches around the globe (Chaloupka et al. 2008), leatherback turtles, *Dermochelys coriacea*, in the Caribbean (Dutton et al. 2005), and loggerhead turtles, *Caretta caretta*, in Brazil (Marcovaldi and Chaloupka 2007). Other populations, however, continue to decline (e.g., loggerheads in the North Pacific; Kamezaki et al. 2003) or show no evidence of recovery (e.g., leatherbacks in the western and eastern Pacific; Chan 2006; Chan and Liew 1996; Santidrián-Tomillo et al. 2007; Sarti Martínez et al. 2007). Further, even those populations with observed increases in the number of nesting females may be experiencing declines in the juvenile life stages (Seminoff and Shanker 2008).

Precise estimates of abundance and survival rates are of critical importance for evaluating the likelihood of population persistence via population viability analysis or for deriving management decisions, e.g., Marine Mammal Protection Act (1972, amended 2007). These parameters are fundamental in modeling and for evaluating population persistence and resilience to anthropogenic mortalities. For species with a wide spatial distribution, however, management decisions at the species level may not be effective due to the variability in the magnitude of each threat (e.g., habitat alteration and fisheries bycatch) at regional and

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local scales. Further, these threats may variably impact the population segments occurring at these different spatial scales such that while some local or regional subpopulations may be stable or increasing over time, others may be decreasing. Each of these subpopulations is a component of the respective ecosystem such that it should be monitored and managed. This is further complicated for highly migratory species with complex life histories. In the case of sea turtles, populations comprise breeding units tied to nesting habitat on tropical beaches which are linked to multiple foraging and developmental habitats, often spread out across ocean basins (Chaloupka et al. 2004; Bowen et al. 2005). The degree of demographic connectivity between these various nesting, developmental, and foraging populations may be unknown, requiring management of these population components at a local, smaller scale than the broader population level.

The green turtles inhabiting San Diego Bay, California (32.6°N, 117.1°W), is an example of a local resident foraging population. The foraging population is one of the northern most of several foraging populations inhabiting bays along the coast of Baja California and mainland Mexico (Koch et al. 2007; Senko et al. 2010). Preliminary results of genetic and satellite telemetry studies indicate that green turtles in San Diego Bay are primarily part of the Mexican breeding population of eastern Pacific green turtles. Likely nesting sites of these turtles include the Revillagigedos Islands, Tres Maria Islands, and mainland Mexico (Fig. 1, Dutton 2003, unpublished data; also see Dutton et al. 2008). Although green turtles have been seen in San Diego Bay since the mid 1800s, consistent reports of sightings ceased after World War I and did not recommence until 1960s (Stinson 1984), which coincided with the opening of a power plant in 1960 that emits warm effluent water (Fig. 1, Duke Energy South Bay, LLC 2004). The effluent creates a thermally unique environment in the southern end of the bay where green turtles assemble during winter (McDonald et al. 1994; Stinson 1984). This concentration of green turtles provides an exceptional study site where continuous tagging and capture-recapture studies have been conducted since the early 1990s.

Using the long-term data set as mark-recapture data, we attempted to estimate life history parameters for the foraging population. Although the recent analytical developments in analysis of capture-recapture data allow us to compute a wide variety of life history parameters, such as immigration, emigration, and recruitment rates (e.g., Arnason 1972; Brownie et al. 1993; Schwarz et al. 1993; Williams et al. 2002), we focused on abundance and survival rates because they relate directly to management decisions. To estimate the abundance of the local foraging population of green turtles, we fitted mark-recapture models to the long-term capture-recapture data. The

principal purpose of this study was to use the longitudinal capture-recapture records of green turtles in San Diego Bay to estimate abundance and survival rates. These estimates are essential in developing management regulations as they relate directly to the viability of the population.

Materials and methods

San Diego Bay is the largest embayment in the Southern California Bight. Open water covers 4,262 ha and tidelands cover 1,788 ha of San Diego Bay. The bay is approximately 25 km in the north–south direction and has 87 km of shoreline (Fig. 1, Lambert and Lambert 2003; Merkel & Associates 2009). The bay's depth ranges from 15.2 to 22.5 m below mean lower low water (MLLW) in the dredged shipping channels in the northern part of the bay, but most of the bay is less than 15 m below MLLW. In the south bay, water depths are on average less than 4.6 m below MLLW (Merkel & Associates 2009). San Diego Bay contains a variety of tidal and subtidal habitats, including 333 ha of salt marsh, 396 ha of tidal flats, 431 ha of eelgrass beds, 73 km of hard substrate and fouling communities, and 3,776 ha of mud and sand bottom assemblages (U.S. Navy 1999). Otay and Sweetwater rivers provide freshwater inputs to the southern bay (Fig. 1). The coastline of the bay is populated with private homes, military bases, shipyards, harbors, hotels, restaurants, and industrial docks. A power plant is located on the southeastern shoreline of San Diego Bay. The plant contains four units,

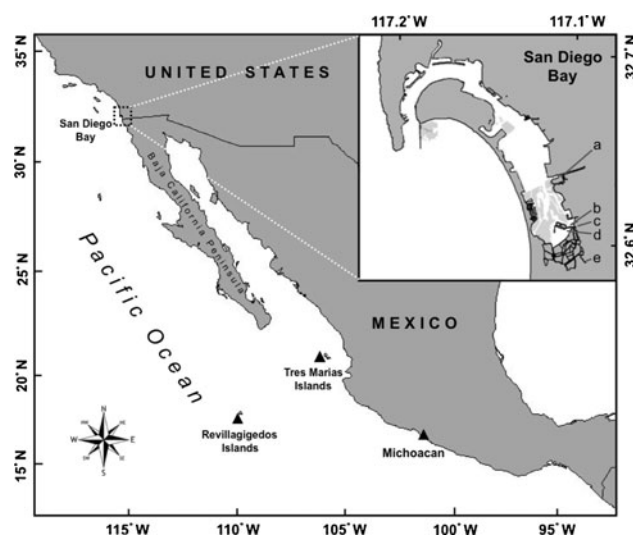


Fig. 1 Maps of the study area in San Diego Bay and known nesting sites for green turtles in Mexico. Gray shaded areas within San Diego Bay indicate known eelgrass habitat. **a** Sweetwater River, **b** intake channel, **c** power plant, **d** effluent channel, **e** Otay River. Likely nesting areas are Tres Maria Islands, Revillagigedos Islands, and Michoacan on mainland Mexico

which can be run independently. The first unit began operations in 1960, followed by other three units in 1962, 1964, and 1971. The power plant uses bay water for cooling their units, and the cooling water is discharged to the bay through the effluent channel.

Green turtles were caught with entanglement nets (50–100 m length \times 8 m depth, mesh size = 40 cm stretched) near the power plant during winter and spring months from 1990 to 2009. The entanglement nets used in this study have been used to capture the smallest of post-pelagic juvenile turtles at other green turtle foraging areas in Mexico (SCL \geq 35 cm; Seminoff et al. 2003). We therefore assumed that all size classes of green turtles living in San Diego Bay would be caught by these nets. Exact locations of nets were dictated by tidal height, which restricted access to some areas during a low tide. All nets were deployed from a Boston whaler (approximately 5 m in length) with a 75-hp outboard motor. The distance of the nets from the shore ranged from approximately 2 to 100 m, whereas water depths ranged from <1 to 6 m.

The beginning of each capture season varied from November to January, and the end of a season ranged from February through May (Fig. 2). One capture attempt was made during August 2004. Capture attempts often were initiated before 0900 h and nets were retrieved before 1500 h, although occasional nighttime captures were attempted. Nets were checked for turtles and other species every hour or less. When a green turtle was caught in a net, it was brought onto the boat, disentangled, and transported to shore for measuring, weighing, and tagging. Straight carapace length (SCL) was measured from the nuchal

notch to the posterior-most portion of the rear marginal scutes using a forester's caliper. Turtles that were caught for the first time were fitted with inconel flipper tags (Style 681, National Brand and Tag Company, Newport, KY, USA) and a passive integrated transponder tag (Avid, Norco, CA, USA), whereas recaptured turtles were identified based on the presence of these uniquely coded tags. All turtles were released within 6 h of capture. Captured turtles on land were kept under a shade and closely monitored. Eyes and carapace were kept moist to avoid overheating.

To estimate abundance and survival probabilities, we used mark-recapture statistical models. We assumed that the group of turtles within the bay was “closed” from deletion (emigration and deaths) and addition (immigration and births) during each winter but “open” between winters (robust-design model, Pollock 1982). In this study, a “birth” refers to the first entry of a turtle to the bay. Parameters were estimated using software MARK (White and Burnham 1999). Using an anonymous reviewer's suggestion, we used a conditional parameterization of the robust-design models, also known as “Huggins closed model” in MARK. In the Huggins robust-design closed model, abundance is computed as a derived parameter. In other words, the statistical model does not contain abundances as explicit parameters. Abundances are computed from estimated capture probabilities and observed data. Although most capture “seasons” extended over two calendar years, we use “years” to describe the time component in the mark-recapture models.

We considered several statistical models that could describe the movements of the turtles and our sampling design. Candidate models were constructed using three general parameter groups; capture probabilities, survival probabilities, and immigration and emigration probabilities (Table 1). We assumed a constant capture probability among individual turtles because it was unlikely that our capture method or turtle behavior would have changed capture probabilities among individuals. For the same reason, capture and recapture probabilities were assumed to be equal. In other words, we assumed that all green turtles in the bay were caught with the same capture probability at any given day regardless of their capture history within a capture season. We think green turtles in the bay were not avoiding the nets because we have experienced multiple captures of the same turtles within one sampling day.

We used water temperature as a potential covariate that affected capture probabilities. This decision was made because of (1) fewer turtles were caught in late spring when the water temperature in the bay was higher than during winter and (2) small numbers of recaptures that made estimations difficult. Water temperature data were recorded at the intake and effluent of the power plant between

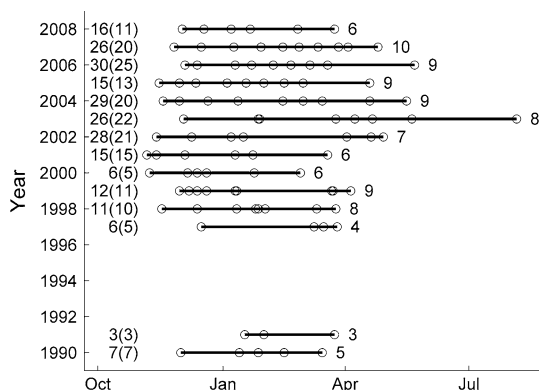


Fig. 2 Sampling dates and sample sizes for the green turtle capture-recapture study in San Diego Bay. The vertical axis indicates the beginning of each sampling season because a season extends over 2 years. The numbers at the left of each line indicate the total number of captured turtles within each season and the number of unique turtles in parentheses. Unique turtles were determined for each season and not for the entire study. The number at the right of each line indicates the number of sampling days in which at least one turtle was caught, which also is indicated by a circle in the plot (secondary samples)

Table 1 Notation and definitions

Parameters	Treatments					
	Symbol	Year	Constant	Temperature	None	Random
Capture probability	p	$p(t)$	$p(\cdot)$	$p(\text{temp})$	n/a	n/a
Survival rate	s	$s(t)$	$s(\cdot)$	n/a	n/a	n/a
Immigration/emigration	γ''	n/a	$\gamma''(\cdot)$	n/a	$\gamma'' = 0$	$\gamma'' = \gamma'$
Immigration/emigration	γ'	n/a	$\gamma'(\cdot)$	n/a	$\gamma' = 0$	$\gamma' = \gamma''$

Parameters are capture and recapture probabilities (p), annual survival rate (s), probability of a turtle not in the bay during a season when it was in the bay during the previous season (γ''), and probability of being outside of the bay in two consecutive seasons (γ'). Abundance was estimated as a derived parameter using capture probabilities and the number of captured turtles. n/a indicates the treatment was not considered

January 1, 2002, and December 30, 2008.¹ A regression analysis was conducted to determine the relationship between intake and effluent water temperatures. If there was a strong linear relationship between them, either intake or effluent temperature would provide sufficient information about the effects of water temperature on capture probabilities if there is one. Because temperature data were not available for every capture day, the monthly averages over 7 years of intake temperatures were used as a linear covariate that affected capture probabilities. Capture probabilities, therefore, were modeled as a function of either (1) years, (2) water temperature, (3) water temperature and years, or (6) constant.

We treated survival rates to be either constant over years or time-dependent. Emigrations and immigrations were modeled in terms of (1) the probability of a turtle remaining outside of the bay for two consecutive years and (2) the probability of a turtle not being present in the bay during 1 year when it was in the bay during the previous year (Kendall et al. 1995, 1997). Temporary emigration and immigration were modeled as either (1) first-order Markov processes, (2) completely random, or (3) none. We constrained these temporary emigration and immigration parameters to be time independent, or constant over time, because the number of parameters for models with time-dependent emigration and immigration would be too large for our data set. A total of 15 models were fitted to the mark-recapture data. The relative fit of a model was determined using AIC_c (Akaike's Information Criterion adjusted for small sample size; Sugiura 1978). To compute 95% confidence intervals, we used the profile-likelihood option in MARK.

To incorporate the uncertainty of the model selection process into our parameter estimates, we used the model averaging method. Differences in AIC_c values were used to compute the model weights, which then were used to estimate the weighted average of the parameters based on the relative importance of the models using MARK.

Uncertainty around a point estimate was expressed by an unconditional standard error (SE) and a 95% confidence interval (95% CI).

Results

From December 2, 1990, to March 25, 2009, a total of 96 individual green turtles were caught 230 times in San Diego Bay during 99 capture sessions (Fig. 2). The majority of individuals were caught three times or less but 10 individuals were caught more than six times (Fig. 3a). Straight carapace lengths (SCL) of captured turtles ranged from 44.0 to 110.4 cm ($\bar{x} = 85.0$, Median = 91.2, SD = 17.3, $n = 210$; Fig. 3b), whereas mass ranged from 12.5 to 241.0 kg ($\bar{x} = 97.7$, Median = 104.0, SD = 52.1, $n = 177$). No capture attempt was made during the 1993/1994, 1994/1995, and 1995/1996 seasons, whereas only one capture attempt was made during the 1992/1993 and 1996/1997 seasons. Consequently, data for the capture seasons 1992/1993 through 1996/1997 were excluded from

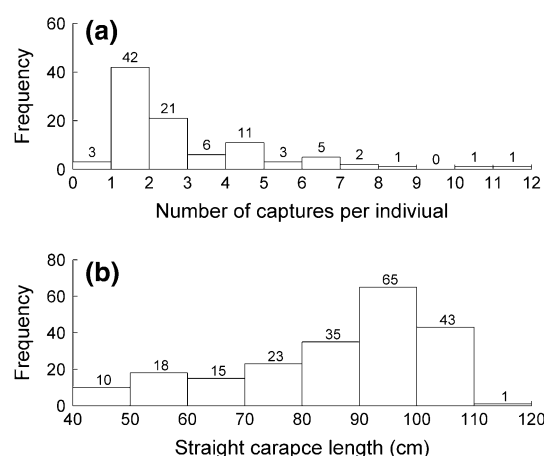


Fig. 3 Frequency histograms of the number of captures (**a**) and straight carapace lengths (**b**) of green turtles that were caught in San Diego Bay from December 2, 1990, to March 25, 2009. In **b**, each capture was treated as a datum, therefore, one individual may be represented multiple times

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the capture-recapture analyses (Fig. 2). For the 1992/1993 and 1996/1997 seasons, one turtle was caught during the 1992/1993 season and three turtles were caught during the 1996/1997 season. For these four turtles, three were caught once throughout the study, whereas one was caught the first time 6 years prior to the 1996/1997 season (February 16, 1991) and recaptured four more times in the subsequent years. Therefore, the loss of information from omitting these two seasons should be minimal.

A regression analysis between intake and effluent water temperatures indicated a linear relationship (slope = 0.94, 95% CI = 0.87–1.03, $r^2 = 0.63$, $n = 366$; Fig. 4a). Because of the linear relationship between intake and effluent temperatures, we use the effluent temperature as a covariate in our analysis. The result would not change if the intake temperatures were used instead.

The first step of mark-recapture analysis should be assessing the appropriateness of fitted models to the data through some measure of goodness-of-fit. In our data set, however, the majority of possible capture histories were not observed due to the small sample sizes. Consequently, the existing goodness-of-fit measures that are based on the asymptotic theory would not be appropriate. Based on our knowledge of the ecosystem in San Diego Bay, we think the models included parameters that affected the annual abundance of green turtles in the area. We discuss the justifications for using the small data set in mark-recapture parameter estimations in the “Discussion” section.

Based on AIC_c , the most parsimonious model included random immigration/emigration and the monthly water

temperature as a covariate for capture probabilities, whereas survival to be constant over time (Table 2). Four other models were $\Delta AIC_c < 4$, indicating that these models also should be considered for the inference process.

A negative relationship was found between the model-averaged capture probabilities and monthly average water temperature (Fig. 4b). The small sample size, however, reduced the precision of estimates, resulting in wide confidence intervals.

Table 2 The seven most parsimonious models and their model selection criteria for the capture-recapture data of green turtles in San Diego Bay from 1990 to 2009

Model	Delta AIC_c	AIC_c weights	Num Par
$p(temp)s(\cdot)\gamma' = \gamma''$	0.00	0.387	4
$p(\cdot)s(\cdot)\gamma' = \gamma''$	0.68	0.276	3
$p(temp)s(\cdot)\gamma'(\cdot)\gamma''(\cdot)$	1.92	0.148	5
$p(\cdot)s(\cdot)\gamma'(\cdot)\gamma''(\cdot)$	2.51	0.110	4
$p(temp)s(t)\gamma' = \gamma''$	3.59	0.064	10
$p(temp)s(\cdot)$	7.62	0.009	3
$p(\cdot)s(\cdot)$	8.58	0.005	2

All models were used to compute the model-averaged abundances. Model parameter definitions are listed in Table 1. Num Par number of parameters

Table 3 Estimated survival rate (s), immigration/emigration rates (γ' and γ''), and abundance (N) of green turtles in San Diego Bay from 1990 to 2009

	Estimate	SE*	CI _L	CI _U
s	0.861	0.147	0.356	0.986
γ'	0.132	0.105	0.025	0.479
γ''	0.153	0.085	0.048	0.395
$N(1990/1991)$	25.8	9.06	8.09	43.60
$N(1991/1992)$	17.6	9.61	0.00	36.44
$N(1997/1998)$	23.4	9.83	4.15	42.69
$N(1998/1999)$	25.5	7.01	11.77	39.26
$N(1999/2000)$	25.7	6.60	12.81	38.68
$N(2000/2001)$	16.0	6.30	3.67	28.36
$N(2001/2002)$	48.7	12.17	24.82	72.52
$N(2002/2003)$	61.2	13.22	35.31	87.16
$N(2003/2004)$	59.4	12.56	34.82	84.06
$N(2004/2005)$	48.4	10.07	28.68	68.15
$N(2005/2006)$	30.6	7.34	16.17	44.93
$N(2006/2007)$	58.9	11.24	36.86	80.91
$N(2007/2008)$	44.0	8.77	26.79	61.18
$N(2008/2009)$	34.9	9.87	15.59	54.28

Estimate is the model-averaged point estimate, SE is standard error, CI_L is the lower bound of 95% CI, and CI_U is the upper bound of 95% CI. Models are listed in Table 1, and the weight of these models for computing the averages is in Table 2

* SE is the unconditional standard error, which incorporates the variation in the estimates across the models

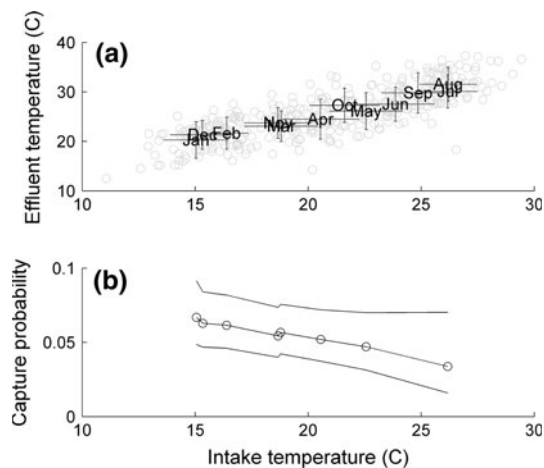


Fig. 4 The relationship between intake and effluent water temperature near the power plant in south San Diego Bay (a) and effects of the temperature on estimated capture probabilities (b). Each gray circle in a indicates a daily measurement, whereas error bars are one standard deviation for each month. Estimates of capture probabilities are model-averaged estimates using AIC_c weights. Circles in b indicate the monthly average temperatures and point estimates of capture probabilities from the mark-recapture models, whereas lines are linear interpolations of 95% confidence limits

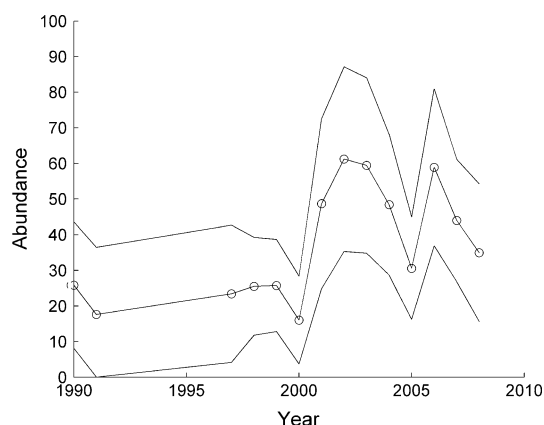


Fig. 5 Estimated abundance of green turtles in San Diego Bay from 1990 to 2009. Circles indicate the model-averaged point estimates, whereas lines without circles indicate 95% confidence limits that are linearly connected (See Table 3 for exact values)

The model-averaged annual survival rate was 0.861 (SE = 0.147, 95% CI = 0.356–0.986). Using the models with emigration and immigration parameters (Table 2), the estimated probability of being absent from the bay in two consecutive years (γ') was 0.132 (SE = 0.105, 95% CI = 0.025–0.479), whereas the estimated probability of being present in the bay in two consecutive years ($1 - \gamma''$) was 0.847 (SE = 0.085, 95% CI = 0.605–0.952). The estimated abundance of green turtles in San Diego Bay ranged from approximately 16 (SE = 6.3, 95% CI = 4–29) during the 2000/2001 capture season to 61 (SE = 13.2, 95% CI = 36–88) during the 2002/2003 capture season (Table 3, Fig. 5).

Discussion

The small number of recaptures added difficulties to the analytical processes, including model selection, goodness-of-fit, and parameter estimations. Small sample sizes also hindered the quantitative assessments of model assumptions. Rather, we used statistical models that fit our knowledge of the ecosystem, sampling process, and biology of green turtles in the area. The longevity of green turtles (Balazs and Chaloupka 2004; Limpus and Chaloupka 1997; Zug and Glor 1999; Zug et al. 2002), their preference for warm water (Spotila et al. 1997), and the lack of nesting in the area suggest that the winter population of green turtles in San Diego Bay is demographically closed on an annual basis. The natural mortality of green turtles within the 4–6 month period during winter and early spring is likely to be negligible because of the longevity of the species. The lack of immigration and emigration of the population during the winter months is supported by the physical oceanography of the area. Generally, sea surface

temperature of the California current along the Southern California Bight and the northern Baja Peninsula during the winter months (November–April) is approximately 14°C (Hickey 1993; Hood 1993; Legaard and Thomas 2006). This water temperature is less than the lower limit of thermal range for green turtles. Further, water temperature in the bay can decrease to <15°C during winter months (Fig. 4a). Green turtles have been observed to become sluggish, cease feeding, or enter dormancy when the water temperature is <15°C (Felger et al. 1976; Moon et al. 1997; Seminoff 2000). Therefore, it is likely that the water mass along the coast line in the northern bay would act as a physical barrier for these turtles in winter, creating a pocket of habitable environment in the southern portion of San Diego Bay, where the power plant effluent results in warmer water temperature. To determine the closure of the foraging unit of green turtles in San Diego Bay, however, mark-recapture data alone probably are not sufficient because of the difficulty obtaining large enough sample sizes. Acoustic and satellite telemetry studies currently are conducted to gather information on movement patterns of green turtles within the bay with respect to the thermal environment in the bay.

The robust-design modeling approach allowed us to estimate the temporary emigration and immigration parameters. Because of the small number of recaptures, however, the precision of the estimates was poor. The reproductive status and environmental conditions of these turtles were likely to affect temporary emigration and immigration. Even though adult females have been known to migrate from San Diego Bay to Mexico for nesting and subsequently returning to the bay, previous satellite telemetry efforts for a few turtles (P. Dutton, unpubl. data) are insufficient for drawing conclusive remarks for the entire population. One adult female turtle tagged with a satellite transmitter migrated from San Diego Bay to the Revillagigedos Islands (Fig. 1) in approximately 3 months, stayed in the vicinity of the islands for 4 months, and returned to the bay 2 months later (Dutton et al. in prep). We suspect that non-reproductive females may remain in the bay over consecutive years. Other factors that may affect the immigration and emigration of these turtles include oceanographic conditions. For example, immigration of juveniles into San Diego Bay may be affected by the thermal environment in the California Current system. It is possible that during El Niño years, more juvenile green turtles may be moving northward from Mexican waters along the west coast of the North America, following the above average sea surface temperature (Hood 1993).

Despite our annual sampling protocol and ongoing telemetry efforts, the movements and residency patterns of green turtles during the warmest summer periods (May–September) are unclear. Anecdotal reports indicate that

green turtles have been found outside the bay during the summer months, although it is unknown whether these turtles originate from San Diego Bay or from other locations. There is a resident green turtle population in Long Beach, CA, approximately 220 km north of San Diego Bay, as well as numerous foraging locations along the Baja California Peninsula to the south. It is possible that turtles found outside the bay either originate from these other foraging areas or are transiting between them during the summer. Nevertheless, we consider these movements to occur exclusively during summer months.

The importance of the bay as a green turtle habitat is more critical during winter when turtles rely on the thermal refuge generated by the power plant effluent. Warmer temperatures are favorable for turtles, enhancing metabolic processes such as digestion and growth. Green turtles in San Diego Bay grow at a fast rate (up to 9.3 cm/year; Dutton and Dutton 1999), which is comparable to the growth rate of green turtles in the Caribbean (Bjorndal et al. 2000). Further, movement patterns of green turtles tagged with temperature sensors indicated a strong diel pattern during winter months (Lyon et al. 2006). During winter, these turtles in San Diego Bay forage outside of the warm effluent plume at night and return to the effluent channel in the morning, allowing for continuous digestion and somatic growth throughout the year. These animals are evidently taking advantage of the modified environment. A similar behavior has been reported for the Florida manatee (*Trichechus manatus latirostris*, Laist and Reynolds 2005a, b).

The negative relationship between water temperature and estimated capture probabilities confirmed our experience in the field (Fig. 3b). Toward the end of each capture season (April–May), the number of captures declined. We have speculated that the warm water temperature throughout the bay at this time of year results in a wider distribution of turtles in the bay. The wider distribution reduces the predictable daily movement to the effluent channel by the turtles in the morning, although turtles have been found in the effluent channel every month of the year except when the water temperature in the effluent becomes $>29.4^{\circ}\text{C}$ (Dutton and McDonald 1990). Further, biofouling of the capture nets by bryozoans (*Zoobotryon* sp.) increases during these months. The biofouling perhaps reduces turtle entanglement rates due to the loss of mesh surface area or by making the nets more visible to turtles.

The annual survival rate estimate of 0.861 (SE = 0.147, 95% CI = 0.356–0.986) was similar to estimates for juvenile green turtles in the Bahamas (0.891, 95% CI = 0.776–0.950, Bjorndal et al. 2003), at the Great Barrier Reef (subadult: 0.85, 95% CI = 0.79–0.91, juveniles: 0.88, 95% CI = 0.79–0.93, Chaloupka and Limpus 2005), at Bahía Magdalena,

Mexico (0.85, 95% CI = 0.83–0.88, Koch et al. 2007), and at Tortuguero, Costa Rica (0.85, 95% CI = 0.8–0.9, Troëng and Chaloupka 2007). Our estimate, however, was less precise than the other studies. The estimated adult survival rate for the Great Barrier Reef population was 0.95 (95% CI = 0.92–0.98, Chaloupka and Limpus 2005), which was significantly greater than estimates for other studies that included juveniles. Our estimate was for post-pelagic juveniles and adults, where the SCL ranged from 44.0 to 110.4 cm SCL. Therefore, our estimate should be considered as the average over a wide range of age classes and included anthropogenic mortality.

Deaths of green turtles in San Diego Bay have been reported to the stranding network annually. Exact causes of deaths are often difficult to determine due to the advanced state of decomposition. Boat-strikes, ghost nets, and fishing line ingestions have been reported as known causes of deaths for green turtles in San Diego Bay (National Marine Fisheries Service, Southwest Regional Office, unpublished stranding report).

Even though the existence of green turtles in San Diego Bay has been known for many years (Stinson 1984), this study is the first to estimate life history parameters for these turtles. This highly urbanized environment continues to host a wide variety of human activities, and effective management of this turtle population will require data on annual abundance and long-term population trends. Our analyses indicate that tens of green turtles consistently are present from the months of October to May in the bay, where the upper limits of 95% CI is as high as 87. The current estimates are lower than the number suggested by anecdotal observations during mid to late 1800s (>100 ; in Stinson 1984) but comparable to the conjecture for 1979 (25–30; Stinson 1984). The accuracy of reports of the abundance during the 1800s is unknown and is impossible to validate the historic abundance of green turtles in San Diego Bay.

The origin of green turtles in San Diego Bay is poorly understood. Stinson (1984) postulated that green turtles first arrived in the 1800s as ‘escapees’ from turtle import vessels. In those days, turtles were brought from Mexico and off-loaded in San Diego Bay. However, small juvenile ‘recruits’ were periodically caught during our study, indicating that green turtles enter the bay under natural conditions. Our observations of small recruits in the bay, coupled with the fact that ocean currents and the fluctuations of sea surface temperatures over geologic timescales have been fairly constant, suggest that green turtles are present in San Diego Bay through natural processes and have been using this temperate foraging habitat for centuries. Once these turtles establish their residency in the bay, they seem to return to or reside in the bay during the subsequent years. Regardless of how these turtles initiated

their residency in the bay, they are a fundamental component of the ecosystem within the bay and should be managed accordingly.

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